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Drought and spring cooling induced recent decrease in vegetation growth in Inner Asia

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A B S T R A C T

The response of vegetation growth to current climate change in Inner Asia (35–55°N, 45–120°E) was investigated by analyzing time series of the Normalized Difference Vegetation Index (NDVI) data from the Advanced Very High Resolution Radiometer (AVHRR) from 1982 to 2009. We found that at the regional scale, the greening trend observed during the 1980s was stalled in the 1990s. Different seasons, however, show different changes and mechanisms. Among the three seasons (spring, summer and autumn), summer has the earliest turning point (from greening to non-greening) in the early 1990s, as a result of summertime droughts, as indicated by Palmer Drought Severity Index (PDSI). Consistent with the change in summer NDVI, summer PDSI and precipitation significantly increased in the 1980s, but strongly decreased since the early 1990s at the regional scale. The negative effect of summer drought is particularly significant over dry regions such as eastern Kazakhstan, Mongolia and Inner Mongolia. However, in high altitude or high latitude regions (>50°N), summer vegetation growth is more strongly correlated with summer temperature rather than with summer PDSI. In spring, changes in vegetation growth are closely linked with temperature changes rather than droughts. Both spring temperature and spring NDVI, for instance, increased until the late 1990s and then decreased. Statistical analyses also show that spring NDVI is significantly correlated with spring temperature at the regional scale ($P < 0.05$), implying that temperature is the dominant limiting factor for spring vegetation growth in most regions of Inner Asia except Turkmenistan and Uzbekistan, where spring PDSI shows significant positive correlation with spring NDVI. Further analyses of the response of vegetation to extreme high spring temperature in 1997 and extreme summer drought in 2001 exhibit a highly heterogeneous pattern.

1. Introduction

At regional and continental scales, many studies based on satellite data have revealed temporal changes in vegetation growth and linkages to climate change (Angert et al., 2005; Goetz et al., 2005; Piao et al., 2011; Wang et al., 2011; Zhou et al., 2001), but most of these were focused on the high latitude regions (Beck et al., 2011; Goetz et al., 2005). There is a dearth of studies on how the ongoing climatic changes have impacted vegetation growth in relatively dry regions. The response of vegetation to these climatic changes will differ across regions depending on the kind of changes experienced and the specific response of regional vegetation to those changes (Donohue et al., 2009).

During the last 30 years, dramatic climate changes have occurred over the drylands dominating in Inner Asia where moisture is one of the most important limiting factors of vegetation growth (Nemani et al., 2003). Climate data from the Climatic Research Unit (CRU) (Mitchell and Jones, 2005) show a significant decrease in precipitation during the growing season, while the trends are highly spatially variable. Furthermore, mean annual temperature over Inner Asia has increased by 0.05 °C yr^{-1} since the 1980s. Such rapid warming could lead to increase in drought stress in this region, since rising temperature will increase evapotranspiration, and hence water loss from the land surface (Abramopoulos et al., 1988; Dai et al., 2004). It is difficult, however, to predict whether vegetation in this region is greening or browning over

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the last three decades, since the potential decrease in soil moisture associated with climate change may be partly compensated by the effect of increasing concentration of atmospheric CO_2 which generally reduces leaf-level stomatal conductance, and thus decreases water loss from the land surface through transpiration (Gedney et al., 2006). Recent studies have shown significant changes in vegetation growth trend in many parts of Inner Asia over the last three decades (e.g., Fensholt et al., 2012; Piao et al., 2011), but its linkage with climate change has not been adequately quantified, because these studies focused mainly on vegetation responses to climate change at regional and continental scales. Therefore, the first objective of this paper is to investigate spatio-temporal changes in vegetation growth over Inner Asia during the last three decades, which will improve our understanding of how vegetation growth will change in the future as drying conditions are projected to expand over the mid-latitudes under climate change in this century (IPCC, 2007).

A key feature of current climate change is the increasing frequency of extreme climate events, particularly heat-waves and droughts (IPCC, 2007). Evidence exists that extreme climate events impact a broad range of ecosystems (Knapp et al., 2008), and have important implications for terrestrial carbon cycle at the regional to continental scales (Ciais et al., 2005; Zeng et al., 2005). Moreover, according to IPCC climate models, it is likely that such extreme events will become more frequent and more intense in the future, although there are considerable uncertainties in climate model predictions (IPCC, 2007). Therefore, understanding and predicting the consequences of the increased incidence of extreme climatic events on ecosystems is emerging as one of the grand challenges for global change scientists (Allen et al., 2010; Knapp et al., 2008). Thus, we further explore how vegetation growth over Inner Asia responded to the extreme climatic events in 1997 and 2001.

2. Data sets and methods

2.1. Study area

The study area (Inner Asia) spans 35–55°N in latitude and 45–120°E in longitude with a total land area of 1.3×10^7 km^2. This region has high landscape heterogeneity with a large altitudinal difference from Tianshan Mountains, where the average altitude is about 5000 m above sea level, to lowland area such as North China plain, where the altitude is mostly below 50 m above sea level (Liu, 2010). This vast study area also has remarkable differences in climatic conditions. The mean annual temperature (MAT) during the study period (1982–2009) generally shows a latitudinal gradient from below −5 °C in Russian Siberia to above 15 °C in Middle Asia and northern China with the exception of high altitude regions (Tianshan Mountain range, Altai Mountain range, Pamir Plateau and the edge of the Tibetan plateau) between 70°E and 100°E showing MAT lower than 0 °C (Figure S1b). There is a precipitation gradient from the pacific coast in the east to the inland regions in the west. Only North China plain and part of Russian Siberia receive mean annual precipitation (MAP) more than 400 mm during the study period, while semi-arid and arid area (MAP < 400 mm) together constitute 82% of the study area. MAP over 39% of the area is even less than 200 mm including the western part of Mongolia and Inner Mongolia, Xinjiang and the Middle Asia area east of the Caspian Sea (Figure S1c). Accordingly, growing season Normalized Difference Vegetation Index (NDVI) shows a spatial gradient similar to the precipitation gradient (Figure S1a). Forests over Russian Siberia (De Fries et al., 1998) have growing season NDVI higher than 0.6, while most shrublands and grasslands over the semi-arid and arid regions (Figure S1d) show growing season NDVI lower than 0.4 (Figure S1a).

2.2. Data sets

Satellite sensor data are increasingly playing a critical role in monitoring changes in vegetation growth. Over the last three decades, several spectral vegetation indices have been developed from satellite data. Among them, NDVI, defined as the ratio of the difference between near-infrared reflectance and red visible reflectance to their sum, has been the most widely used in global and regional assessments of spatio-temporal change of variables related to vegetation greenness and carbon storage in above-ground vegetation (e.g., Myneni et al., 2001; Zhou et al., 2001). The biweekly NDVI dataset used in this study was generated from the NOAA/AVHRR (the National Oceanic and Atmospheric Administration's Advanced Very High Resolution Radiometers) onboard a series of NOAA satellites (NOAA 7, 9, 11, 14, 16, 17 and 18) with a 1:30 or 2:30 PM local daytime overpass time at launch (Tucker et al., 2005). During the pre-processing, data with large solar zenith angle (>40°) were excluded (Tucker et al., 2005) and maximum value composite algorithm (Holben, 1986) was used to obtain NDVI for each two week period. A series of calibration steps were then performed to alleviate known limitations of the AVHRR measurements induced by intersensor calibration, orbital drift and atmospheric contamination (e.g., volcanic aerosols) (Pinzon et al., 2005; Tucker et al., 2005), resulting in the continuous 28 year Global Inventory Monitoring and Modeling Studies (GIMMS) NDVI dataset, called NDVI 3rd generation (NDVI3g).

Monthly mean land surface air temperature and precipitation data at 0.5° resolution were obtained from the Climatic Research Unit, University of East Anglia (Mitchell and Jones, 2005), while monthly Palmer Drought Severity Index (PDSI) at 2.5° × 2.5° resolution were obtained from the University Corporation for Atmospheric Research (Dai, 2011).

2.3. Analyses

Growing season NDVI was defined as the average of NDVI from April to October each year (Zhou et al., 2001). The pixels with mean growing season NDVI < 0.05 were masked as non-vegetated area. The growing season was divided into three seasons: spring (April and May), summer (June–August) and autumn (September and October). NDVI of spring, summer and autumn were calculated as the average of NDVI during the corresponding months. Monthly climate data (temperature, precipitation and PDSI) were used to derive the average of growing season and average of different seasons using the same method applied to monthly NDVI.

The growing season and seasonal NDVI anomaly in a given year of each pixel was defined as standardized departure (σ_{NDVI}) following Eq. (1):

$$\sigma(i) = \frac{\mathrm{NDVI}(i) - \mathrm{Mean(NDVI)}}{\mathrm{Std(NDVI)}} \quad (1)$$

where NDVI(i) is the growing season or seasonal NDVI for year i, and Mean(NDVI) and Std(NDVI) are the average and standard deviation of corresponding NDVI during 1982–2009. To indicate the magnitude of the anomalies, we defined moderate anomalies as $|\sigma(i)| \le 1$, large anomalies as $1 < |\sigma(i)| \le 2$, and extreme anomalies as $|\sigma(i)| > 2$. The growing season and seasonal anomalies of temperature (σ_{Tmp}) and precipitation (σ_{Pre}) were defined using the same method. The magnitude of drought was defined by PDSI value (Palmer, 1965). Moderate drought referred to PDSI value between −4 and −2, and extreme drought referred to PDSI value below −4.

The trend of NDVI and climate variables (temperature, precipitation and PDSI) during a given period (e.g., 1982–2009, 1990–2009 and 2000–2009) was obtained from least square linear regression against the time series of corresponding years. We further used a persistence index to illustrate the change in the NDVI trends (Zhou et al., 2001). In calculating the persistence index, we first estimated NDVI trends for 12 periods: 1982–1987, 1982–1989, 1982–1991, . . ., 1982–2009 and used trend(i) to indicate the trend in the ith period. A score of 1 was given if the absolute value of trend(i) (|trend(i)|) is larger than 80% of |trend($i-1$)| and trend(i) shared the same sign as trend($i-1$); otherwise, the score was 0 for period i. The sum of the score for each period was the persistence index, ranging from 0 to 11. A persistence index of 8 or more was termed as "high persistence" when trends had the same sign during at least 80% of the periods and were comparable in magnitude with the trend during the previous period, while "low persistence" referred to persistence index of 4 or less. Persistence index between 4 and 8 was termed as "medium persistence".

To further explore the climatic factors driving NDVI change, interannual correlations between NDVI and climatic variables (temperature and PDSI) were calculated with the Pearson correlation analysis after removing the linear trend during 1982–2009 from NDVI, temperature and PDSI respectively. To perform the correlations in a spatially explicit form, climate data were resampled into the grid resolution of NDVI data (10 km) using bilinear interpolation method. Although interpolation matches the grid of NDVI and climate datasets, it does not reduce the uncertainties of PDSI spatial variations in tens of kilometer scale due to the coarse spatial resolution (2.5° × 2.5°) of PDSI dataset.

3. Results

3.1. Change in vegetation growth at the regional scale

3.1.1. Change in growing season NDVI at the regional scale

Fig. 1 shows changes in growing season (from April to October) mean NDVI and climate variables (temperature, precipitation, and PDSI) over the study region from 1982 to 2009. Overall, a significant increase in growing season NDVI at the rate of 5×10^{-4} yr^{-1} is observed during the whole study period ($R^2 = 0.25$, $P < 0.01$). However, from the 5-year moving average curve (Fig. 1a), we find that the growing season NDVI does not persistently increase during the entire study period. The increasing trend is most pronounced during the 1980s, and it stalled since the 1990s (Fig. 1a), which is consistent with the changes in PDSI during the same period. As shown in Fig. 1d, PDSI significantly ($P < 0.05$) increased from 1982 to 1994, and then decreased due to significant decrease in growing season precipitation (Fig. 1c).

Besides the change in spatially mean growing season PDSI, the fraction of land area with drought events (defined as growing season PDSI < −2) also shows significant changes. For example, the area experiencing drought significantly decreased from 26% in 1982 to 4% in 1990, and then increased to 35% in 2009 (Fig. 1d). Accordingly, the land area showing negative NDVI anomalies ($\sigma_{NDVI} < 0$) dramatically decreased from 76% in 1982 to 36% in 1990, and then increased to 44% in 2009 (Fig. 1a). The rapid increase in land area showing negative anomalies ($\sigma_{NDVI} < 0$) since 1990 is mainly contributed by the change in land area showing relatively large negative anomalies ($\sigma_{NDVI} < -1$) rather than moderate negative anomalies ($0 < \sigma_{NDVI} < -1$), which does not show significant change during 1990–2009 (0.01% yr^{-1}, $P = 0.67$). Over the last two decades, land area showing relatively large negative anomalies ($\sigma_{NDVI} < -1$) increased from 7% in 1990 to 20% in 2009 (Fig. 1a).

3.1.2. Change in seasonal NDVI at the regional scale

In this section, we look at change in vegetation growth and climatic variables for three seasons: spring (April and May), summer (June–August), and autumn (September and October). Consistent with the vegetation growth change detected from the growing season NDVI, all three seasons not only show generally increasing trend of vegetation growth from 1982 to 2009, but also exhibit significant change in the trend of vegetation growth during the study period (Fig. 2). Among the three seasons, summer shows the smallest and weakest increasing trend of NDVI from 1982 to 2009 (4×10^{-4} yr^{-1}, $R^2 = 0.13$, $P = 0.06$), due to earliest stall of increasing trend of NDVI in the early 1990s (Fig. 2e). Since 1990, summer NDVI significantly decreased by -5×10^{-4} yr^{-1} ($R^2 = 0.24$, $P = 0.03$), while no apparent trend was seen in both spring ($R^2 < 0.01$, $P = 0.94$) and autumn ($R^2 = 0.13$, $P = 0.12$) NDVI. As shown in Fig. 2a and i, the tipping point of change in spring and autumn NDVI occurred in late and mid 1990s. Similar temporal changes of vegetation growth are also observed from the analyses of the change in land area showing negative (or positive) anomalies.

These varying NDVI changes between seasons are partly related to the varying seasonal climate changes. In spring, the stalled increasing trend of NDVI in the late 1990s may be more closely linked with the change in temperature rather than precipitation and PDSI at the regional scale. As shown in Fig. 2b, spring temperature increased until the late 1990s, and then slightly decreased, which paralleled spring NDVI change. Changes in spring PDSI trend occurred in the early 1990s. Further statistical analyses also suggest that in addition to trend, the interannual variation of spring NDVI is also more strongly correlated with spring temperature ($R = 0.49$, $P = 0.01$) rather than with spring PDSI ($R = 0.07$, $P = 0.70$) at the regional scale.

Summer vegetation growth is not strongly regulated by temperature at the regional scale. The partial correlation analysis suggests that interannual variation in summer NDVI is not significantly correlated with the change in summer temperature ($R = 0.11$, $P = 0.60$), after statistically removing the confounding effect of summer PDSI. In contrast, a significant correlation between summer NDVI and summer PDSI ($R = 0.56$, $P < 0.01$) is observed after statistically removing the confounding effect of summer temperature. Furthermore, both summer PDSI trend and summer precipitation trend exhibit corresponding changes in the early 1990s (Fig. 2g and h). The strong decrease in summer PDSI since the early 1990s may be not only related to the rising summer temperature, but also associated with summer precipitation change, which at the regional scale, significantly decreased from 1990 to 2009 (−0.94 mm yr^{-1}, $R^2 = 0.24$, $P = 0.03$).

Autumn also experienced increase in drought events during the recent decades. For example, the average autumn PDSI in 2000s (−0.81) is twenty times of that in the 1980s (−0.04). In addition, the land area with drought events (PDSI < −2) doubled from 15% in 1980s to 30% in 2000s. Although both autumn NDVI trend and autumn PDSI trend show similar change (initial increase and then a decrease), the statistical analysis shows a weak interannual correlation between autumn NDVI and autumn PDSI at the regional scale ($R = 0.27$, $P = 0.16$). Interannual variation in autumn temperature is also not significantly correlated with that in autumn NDVI ($R = 0.19$, $P = 0.34$). Interestingly, there is a significant relationship between autumn NDVI and summer NDVI ($R = 0.60$, $P < 0.01$), implying that autumn vegetation growth is partly dependent on the vegetation growth during the summer.

3.2. Spatial patterns of vegetation growth change

3.2.1. Spatial patterns of growing season NDVI change

The trend in growing season NDVI from 1982 to 2009 exhibited a heterogeneous pattern (Fig. 3a). Although more than half (67%) of the study area showed an increasing trend in growing season NDVI, this trend is statistically significant over only 26% of the area, which is mainly concentrated in the plains of North China, the forested area between 50°N and 55°N to the west of Baikal lake, southeastern Kazakhstan and Kyrgyzstan, and the western coast of the Caspian Sea (Fig. 3a). The persistence indices over these regions

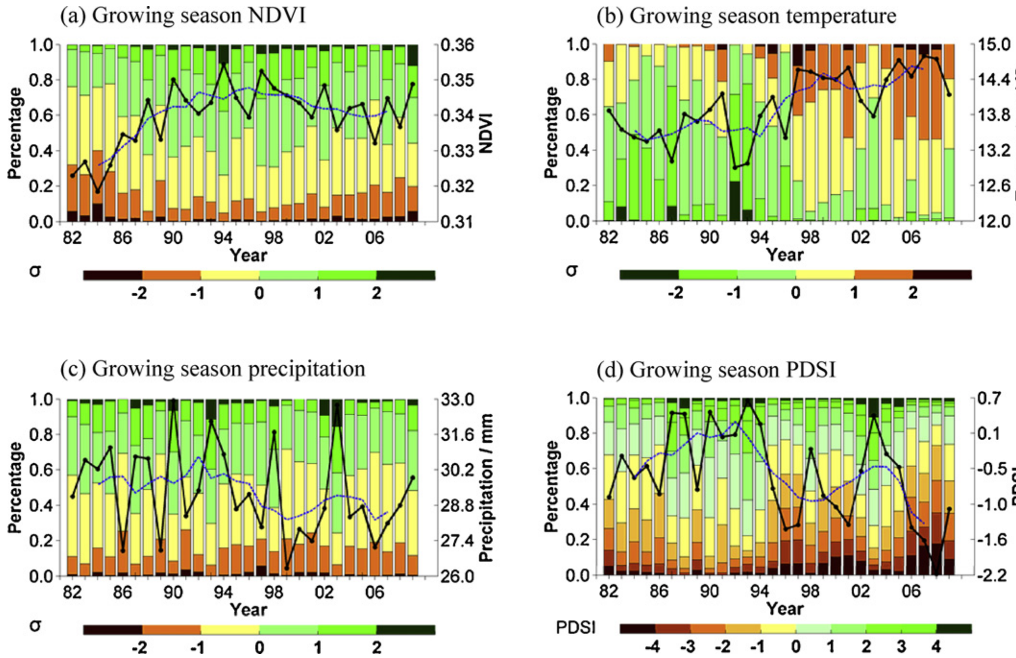

Fig. 1. Interannual variations in growing season (April–October): (a) normalized difference vegetation index (NDVI), (b) temperature, (c) precipitation and (d) Palmer Drought Severity Index (PDSI) over Inner Asia (45–120°E, 35–55°N) during 1982–2009. Solid black lines represent the area-average growing season NDVI and climate, and blue dashed lines represent 5-year running-means. The background color bars represent fractional land area exhibiting different NDVI anomalies (σ_{NDVI}), temperature anomalies (σ_{Tmp}) and precipitation anomalies (σ_{Pre}) and PDSI. σ_{NDVI}, σ_{Tmp}, and σ_{Pre} for each pixel in each year are calculated according to Eq. (1), and binned into moderate ($|\sigma| < 1$), large ($1 < |\sigma| \leq 2$) and extreme ($|\sigma| > 2$) anomalies. PDSI is binned according to its original classification (Palmer, 1965). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

are larger than 8, suggesting a persistent increase in growing season NDVI during the last three decades (Fig. 3d). However, the increasing rate of NDVI slowed since 1990 over most of these regions, except for parts of the North China plain (Fig. 3b).

Unlike earlier studies (e.g., Zhou et al., 2001; Slayback et al., 2003) showing negligible area over mid to high latitudes of the northern hemisphere with decreasing trend, we found that 8% of the study area exhibited significant ($P < 0.05$) decreasing trend in growing season NDVI during 1982–2009, mostly in grasslands over Mongolia, eastern Inner Mongolia, and shrublands over eastern Caspian Sea (Fig. 3a). It should be noted that, however, the decreasing trend over all these regions showed low persistency (persistence index < 4), indicating that a reversal of the initial greening trend could have taken place before the mid-1990s. This is manifested in Fig. 3b – these regions exhibited decreasing trend mostly between -2×10^{-3} yr^{-1} and -4×10^{-3} yr^{-1}, and some area in eastern Inner Mongolia showed even a more rapid decline ($<-5 \times 10^{-3}$ yr^{-1}) during 1990–2009.

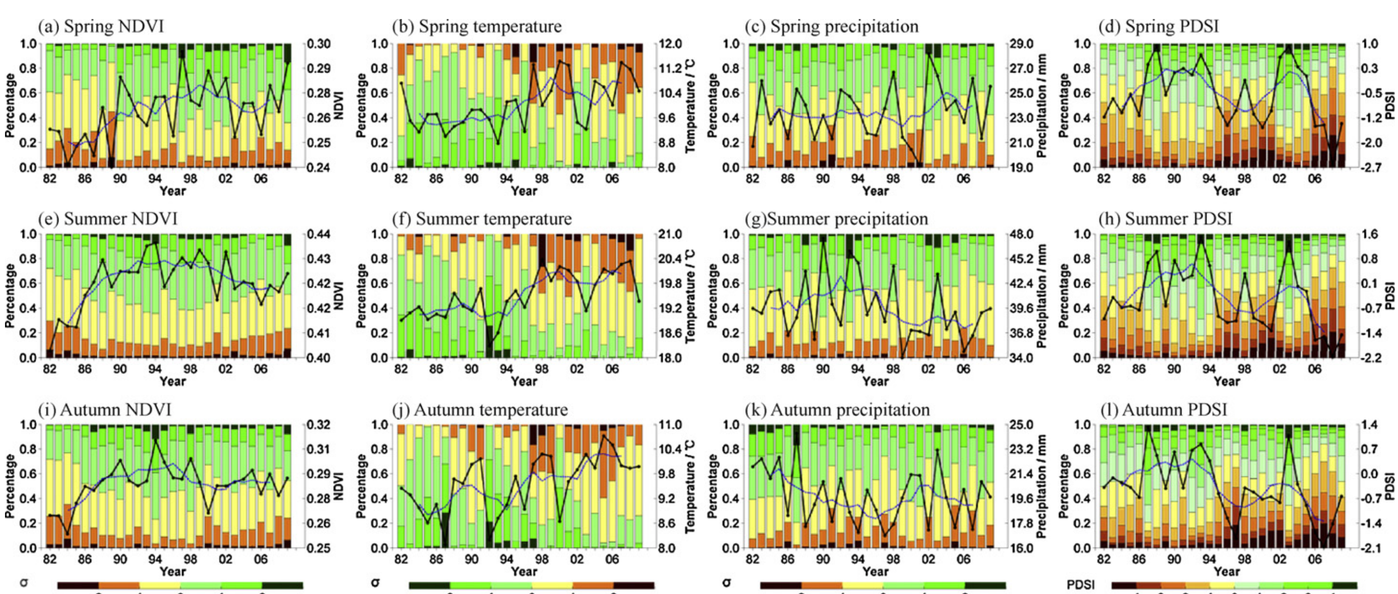

Fig. 2. Interannual variations in seasonal NDVI, temperature, precipitation and PDSI over Inner Asia during 1982–2009. Interannual variations in (a) spring (April–May) NDVI, (b) spring temperature, (c) spring precipitation, and (d) spring PDSI; (e–h) same as (a–d) but for summer (June–August), (i–l) same as (a–d) but for autumn (September–October). Symbols and color codes are the same as in Fig. 1. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

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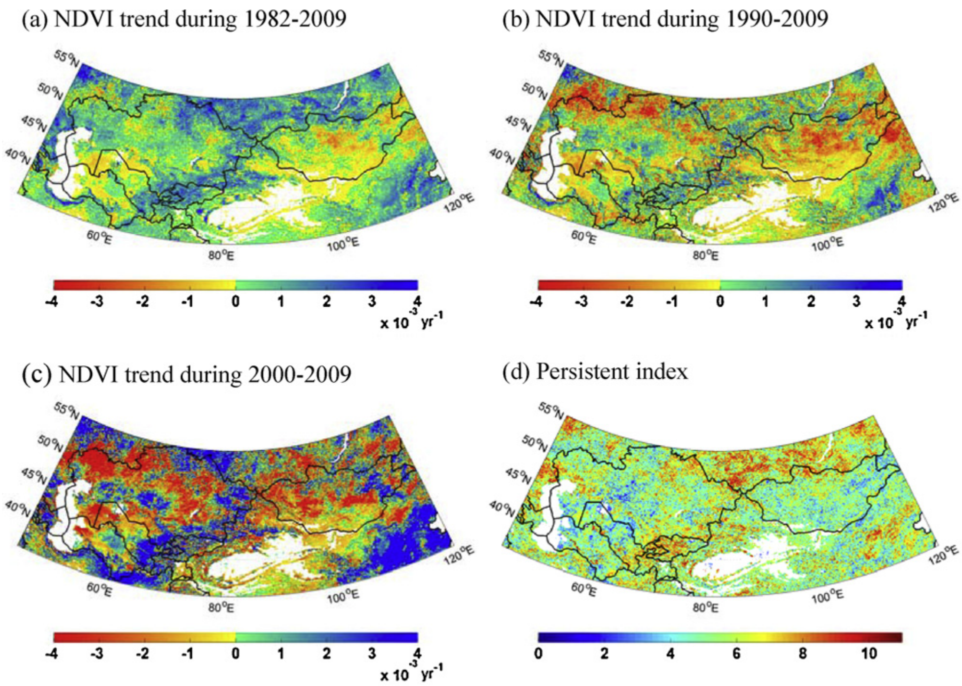

Fig. 3. Spatial distribution of growing season NDVI trends over Inner Asia during the period: (a) 1982–2009, (b) 1990–2009, and (c) 2000–2009, and (d) the persistence index during 1982–2009. High persistence index (larger than 8) is shown in red, while low persistence index (lower than 4) is shown in blue. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

In addition, some areas not showing significant change during the last three decades could exhibit a large decreasing trend during the recent one or two decades. For example, the grasslands between northern Kazakhstan and northern Caspian Sea showed insignificant change during 1982–2009 (Fig. 3a), but the decreasing rate in growing season NDVI could exceed $4 \times 10^{-3}\,yr^{-1}$ since 1990 (Fig. 3b). Overall, the area (67%) showing insignificant change during the last three decades is consistent with the area (67% of the study area) showing medium persistence in the trend (persistence index between 4 and 7), suggesting that changing sign or magnitude of the initial greening trend is prevalent between the mid 1990s and the early 2000s. Indeed, the decreasing trend expanded from 33% of the study area during 1982–2009 to 61% during 1990–2009 (Fig. 3b), and slightly shrunk to 54% during the recent decade (2000–2009) (Fig. 3c).

3.2.2. Spatial patterns of seasonal NDVI change

NDVI trends for different seasons allow better understanding of the phenomenon of growing season NDVI change described in Section 3.2.1. The percentage of area showing increasing trend of NDVI from 1982 to 2009 is larger in spring (70%) than that in summer and autumn (58% and 57% respectively), but all three seasons show that the area experiencing increasing trend during 1990–2009 (50% for spring, 38% for summer and 36% for autumn) is roughly 20% smaller than that derived from the whole study period. The contribution of seasonal NDVI trend to the overall growing season NDVI trend has regionally different features (Fig. 4). The area characterized by significant increase of growing season NDVI (e.g., Northern China plain, the forested area between 50°N and 55°N to the west of Baikal lake, grasslands over south-eastern Kazakhstan and Kyrgyzstan, and the western coast of the Caspian Sea) (Fig. 3a) shows significant increasing trend in all three seasons, but the most pronounced increase in NDVI occurred in spring (Fig. 4a). Furthermore, the trend persistence over these regions is also highest in spring (Fig. 4d), with the increasing rate during 1990–2009 and 2000–2009 still above $4 \times 10^{-3}\,yr^{-1}$ (Fig. 4b and c). The relatively low trend persistence of NDVI during summer and autumn is observed over these regions (Fig. 4h and l).

The regions with a significant decrease in growing season NDVI (Mongolia, eastern Inner Mongolia, and eastern Caspian Sea) show that the decreasing trend of NDVI is most obvious in summer (Fig. 4e), followed by autumn (Fig. 4i). The persistence indices of NDVI trend during these two seasons are also low over these regions (generally ranging from 2 to 4), partly because of the decreasing NDVI trend during 1990–2009 (Fig. 4f and j). For example, in parts of Mongolia and northeastern China, summer and autumn NDVI decreased by more than $5 \times 10^{-3}\,yr^{-1}$ over the last two decades (Fig. 4f and j). In addition, the decrease of summer and autumn NDVI seems to have accelerated in the shrublands over the eastern Caspian Sea area, where the decreasing rate of NDVI is two times larger during 2000–2009 (Fig. 4g and k) than during 1990–2009.

3.2.3. Spatial patterns of interannual correlation between NDVI and climate

Fig. 5 shows the spatial distribution of the interannual correlation coefficients between growing season NDVI and growing season climate (temperature and PDSI). There is a clear regional contrast between the dominant climate factors underlying the observed changes in growing season NDVI. Across the Russian territory of the study area (e.g., northern area with latitudes greater than 50°N), growing season NDVI is significantly and more strongly correlated with growing season temperature rather than growing season PDSI (Fig. 5), implying that temperature is the dominant climatic factor limiting vegetation growth in these relatively cold regions (MAT < 0 °C, Figure S1b). Annual precipitation is generally higher than 400 mm in these regions (Figure S1c). Similar temperature control of vegetation growth could also be found in high altitude regions, such as the Altai Mountains, Tianshan Mountains and Pamir Plateau (Fig. 5). On the contrary, over the vast semi-arid and arid regions in western China and Middle Asia, there is a significant positive correlation between growing season NDVI and growing season PDSI, rather than growing season temperature. Overall, 11%

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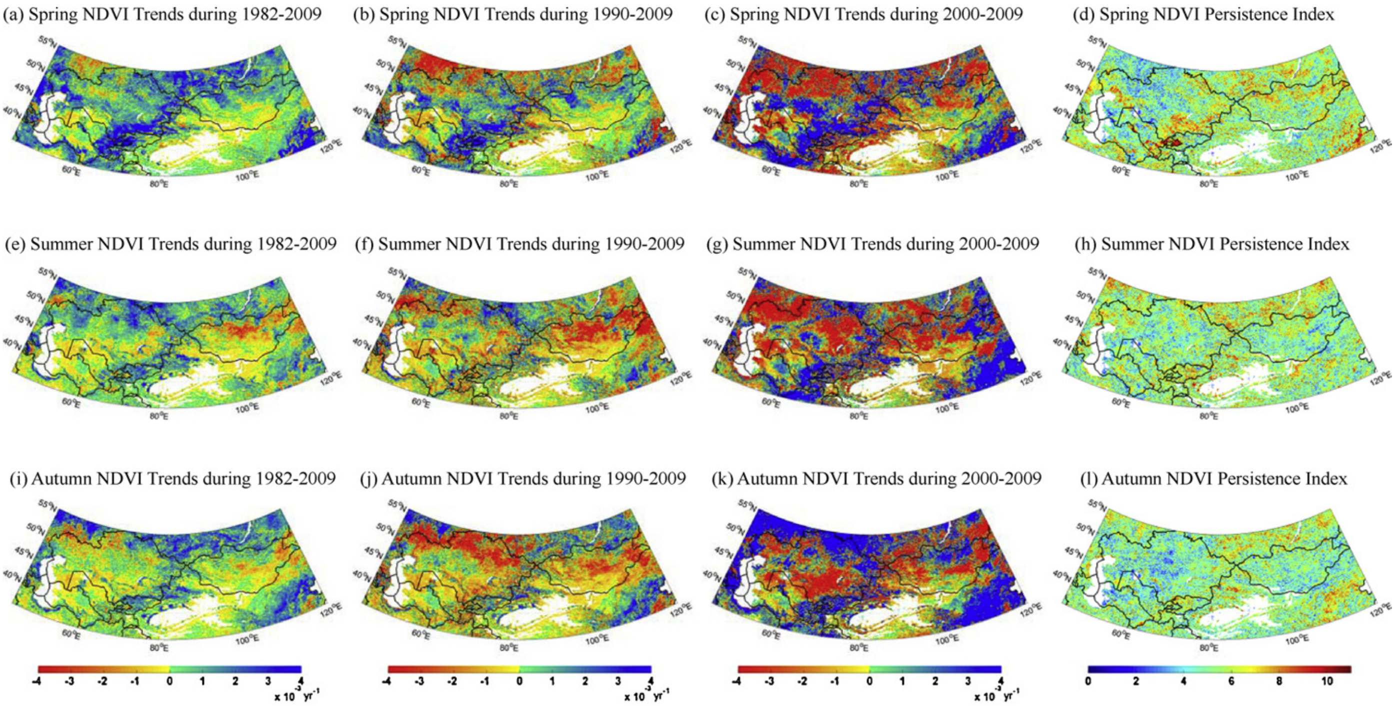

Fig. 4. Spatial distribution of seasonal NDVI trends over Inner Asia during the period 1982–2009, 1990–2009, and 2000–2009, and persistence index during 1982–2009. Spring NDVI trend during the period (a) 1982–2009, (b) 1990–2009, and (c) 2000–2009, and (d) its persistence index during 1982–2009; (e–h) same as (a–d) but for summer NDVI; (i–l) same as (a–d) but for autumn NDVI.

of the study area has significant positive interannual correlation of growing season NDVI with growing season temperature, while growing season NDVI over the 41% of the study area is significantly and positively related with growing season PDSI. However, it should be noted that such relationships between growing season NDVI and climate could have masked seasonally varying vegetation responses to climate change. We thus examine the linkage between seasonal NDVI and seasonal climate for spring, summer and autumn, separately.

In spring, temperature is the dominant factor controlling vegetation growth across most of the study area (Fig. 6a). More than 71% of the study area (e.g., Altai Mountains, Tianshan Mountains and Pamir Plateau) show positive correlation between NDVI and temperature, and 35% of the study area exhibit a statistically significant positive correlation, particularly in the high latitude regions (north of 50°N). This close linkage between temperature and NDVI in spring and the current spring cooling trend

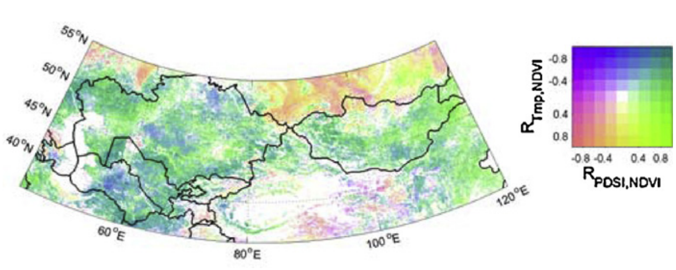

Fig. 5. Spatial distribution of the interannual correlations between growing season NDVI and growing season temperature ($R_{\mathrm{Tmp,NDVI}}$), and growing season PDSI ($R_{\mathrm{PDSI,NDVI}}$) for the period 1982–2009. Each color corresponds to a unique combination of $R_{\mathrm{Tmp,NDVI}}$ and $R_{\mathrm{PDSI,NDVI}}$ shown in the color legend on the right. $R_{\mathrm{Tmp,NDVI}}$ and $R_{\mathrm{PDSI,NDVI}}$ are calculated after removing the linear trend during 1982–2009 from growing season NDVI, temperature and PDSI respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

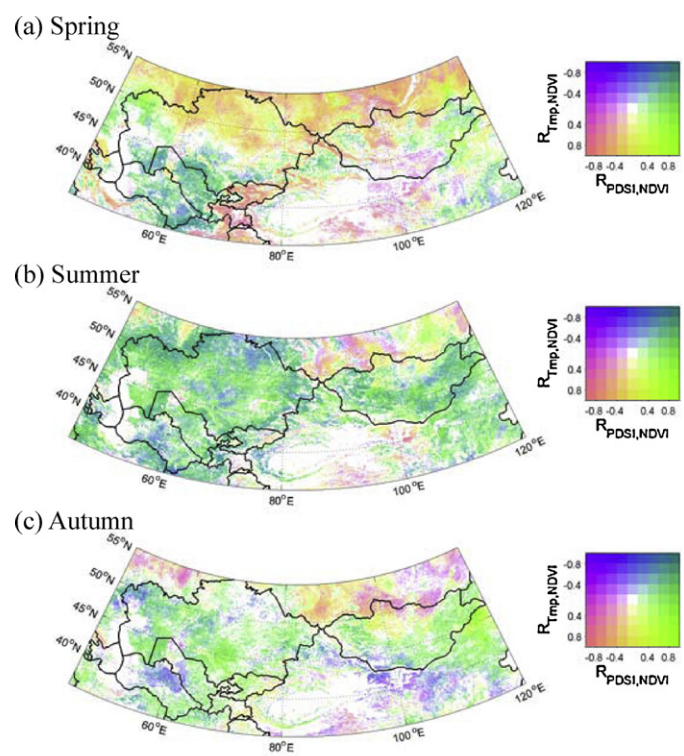

Fig. 6. Spatial distribution of the interannual correlation between seasonal NDVI and seasonal temperature ($R_{\mathrm{Tmp,NDVI}}$), and seasonal PDSI ($R_{\mathrm{PDSI,NDVI}}$) in (a) spring, (b) summer, and (c) autumn during 1982–2009. Color codes are the same as in Fig. 5 and shown in the color legend on the right. $R_{\mathrm{Tmp,NDVI}}$ and $R_{\mathrm{PDSI,NDVI}}$ are calculated after removing the linear trend during 1982–2009 from seasonal NDVI, temperature and PDSI respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

over northwestern Kazakhstan (Figure S2d–f) could explain the decreasing trend of spring NDVI over these regions during the recent decades (Fig. 4a–c). Interestingly, in Turkmenistan and Uzbekistan, spring PDSI shows significant positive correlation with spring NDVI (Fig. 6a), suggesting that vegetation growth over these regions was strongly regulated by moisture conditions.

In contrast to springtime variations, summertime temperature has significantly (positive) correlation with summer NDVI in only 6% of the study area (e.g., part of the Siberia area north of 50°N). Summer NDVI is positively correlated with summer PDSI in more than 82% of the study area, and 48% of the study area exhibit statistically significant correlation, particularly in the grasslands and shrublands over northern and eastern Caspian Sea, eastern Kazakhstan, Mongolia and Inner Mongolia. Considering the drought regulation of vegetation growth in summer over these semi-arid and arid regions and the rapidly decreasing summer PDSI (Figure S4g), the decreasing summer NDVI over these regions (Fig. 4e) is not surprising. On the other hand, in the high altitudes and high latitudes (>50°N), summer NDVI does not show significant correlation with summer PDSI, but is significantly positively correlated with summer temperature (Fig. 6b).

In autumn, the signs of the NDVI-climate relationships are similar to that of summer, but the correlations are weaker. Positive correlation between autumn NDVI and autumn PDSI still dominates in the semi-arid and arid area (71% of the study area), but are statistically significant in only 21% of the study area, mainly over southern and western Kazakhstan, eastern Mongolia and the eastern Inner Mongolia. Only 7% of the study area, mainly in the boreal region to the north of Mongolia, show a significant positive correlation between autumn temperature and autumn NDVI (Fig. 6c). This suggests that the benefit from autumn warming on vegetation growth is not a widespread phenomenon in Inner Asia.

3.3. Response of vegetation growth to high spring temperature and summer drought

In this section, we report analysis of anomalies of spring NDVI in 1997, the year when a large area (15%) experienced extreme high ($\sigma_{Tmp} > 2$) spring temperatures, and anomalies of summer NDVI in 2001, the year when a large area experienced extreme summer drought, to further explore the spatial patterns of high spring temperature and summer drought effects on vegetation growth, respectively.

3.3.1. Response of spring vegetation growth to high spring temperature in 1997

Nearly 50% of the study area experienced high spring temperature ($\sigma_{Tmp} > 1$), including the entire Siberian region north of 50°N, eastern Mongolia, northern Xinjiang, and eastern and central Kazakhstan (Fig. 7b). Among these, some regions (15% of the study area), such as northern Xinjiang, eastern Kazakhstan and its neighboring Siberian region, and the Siberian region north of Mongolia, even showed extreme high temperature anomalies ($\sigma_{Tmp} > 2$). As shown in Fig. 7a, in response to this relatively high spring temperature in 1997, spring vegetation growth strongly increased. About half of the regions experiencing high spring temperature anomalies ($\sigma_{Tmp} > 1$) showed high positive NDVI anomalies ($\sigma_{NDVI} > 1$), while 36% of the regions (e.g., parts of the Siberian regions) experiencing extreme spring temperature anomalies ($\sigma_{Tmp} > 2$) have large NDVI ($\sigma_{NDVI} > 2$) anomalies (Fig. 7a and b). In contrast, in some parts of western Mongolia, a negative anomaly of vegetation growth occurred during the spring in 1997, although both temperature and precipitation showed positive anomalies (Fig. 7b and c). This could be due to potential drought stress induced by higher temperature. Indeed, in this region, large negative spring PDSI anomalies are detected in 1997 (Fig. 7d).

3.3.2. Response of summer vegetation growth to summer drought in 2001

An intense summer drought (PDSI < −2) occurred in 2001 over 43% of the study area including the North China plain, Inner Mongolia, most of Mongolia, central and southwestern Kazakhstan, Uzbekistan, Turkmenistan, Iran and the western coastal area of the Caspian Sea. In Inner Mongolia, southern Turkmenistan, and Iran, the negative anomalies of summer PDSI are even smaller than −4. From Fig. 8c and d, it is apparent that this severe summer drought over the eastern part of the study region (Mongolia and Inner Mongolia) is the synergistic effect of both warmer temperature and lower precipitation. In Middle Asia, precipitation anomalies are moderate, and thus the extreme summer drought could be associated with the high temperature induced increase in evapotranspiration demand. Consistent with the summer drought signal in 2001, widespread negative anomalies of summer NDVI are observed over these regions, particularly the semi-arid and arid areas, such as Inner Mongolia, Central Mongolia, Uzbekistan, Turkmenistan and Iran, where σ_{NDVI} is generally less than −1 (Fig. 8a).

4. Discussion

Previous studies based on remote sensed NDVI data reported a significant greening trend over the middle and high latitudes during the 1980s and 1990s (e.g., Myneni et al., 1997; Zhou et al., 2001), as a result of rising atmospheric CO_2 concentration and climate change (Lucht et al., 2002; Piao et al., 2006). Model simulations projected that the increasing trend in vegetation productivity could last at least till 2050 (Cramer et al., 2001). However, recent observations seem to contradict such predictions, as stalled or decreasing trends of NDVI are observed in the recent decade (e.g., Angert et al., 2005; Gobron et al., 2010; Park and Sohn, 2010; Piao et al., 2011). This is supported by findings in this study. Our results show that at the regional scale, growing season NDVI in Inner Asia has significantly increased during the whole study period ($R^2 = 0.25$, $P < 0.01$), but this increasing trend mainly occurred during the 1980s.

Unfortunately, much less is known about the mechanisms responsible for the current stalled or decreased NDVI trend during the last decade. Angert et al. (2005) suggested that recent vegetation browning may be related to increasing summertime drought stress, while Wang et al. (2011) argued that a springtime cooling trend is the primary driver of the decrease in vegetation growth over the northwestern North America. Our results indicate that both mechanisms could have contributed to the change in vegetation growth in Inner Asia. As shown in Fig. 4a and e and Figures S2d and S4g, in consistent with the trend of spring cooling and summer drought, both spring and summer NDVI show decreasing trend over the last decades.

Although it has been suggested that water is the limiting factor for vegetation growth in the semi-arid and arid Inner Asia (Nemani et al., 2003), the results presented in this study show that different seasons could have different limiting factors. At the regional scale, there is a significant positive correlation between spring NDVI and spring temperature, which is higher than the correlation between spring NDVI and spring precipitation and between spring NDVI and spring PDSI. This result indicates that temperature is the dominant climatic factor regulating spring vegetation growth over the study area. The enhancement of spring vegetation growth in response to rising spring temperature may be related to warming induced earlier spring vegetation phenology. Several studies have highlighted the linkage between phenology and vegetation productivity (Richardson et al., 2010). For example, an increase in

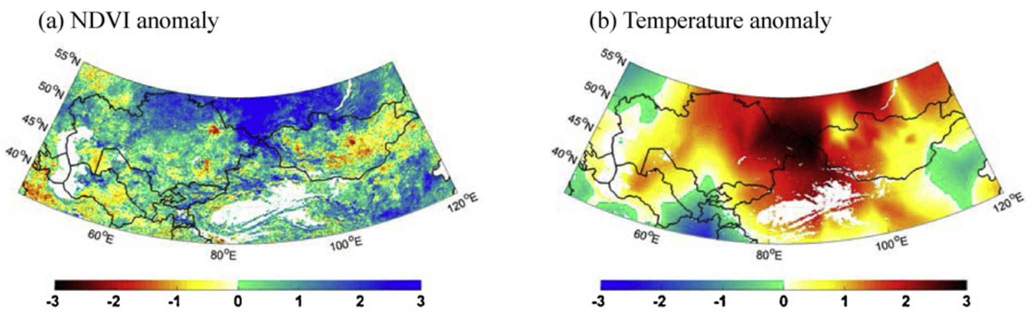

Fig. 7. Spatial distribution of (a) NDVI anomalies (σ_{NDVI}), (b) temperature anomalies (σ_{Tmp}), (c) precipitation anomalies (σ_{Pre}), and (d) PDSI in spring 1997. σ_{NDVI}, σ_{Tmp} and σ_{Pre} for each pixel are calculated according to Eq. (1).

annual Net Primary Productivity (NPP) in response to earlier spring plant emergence in boreal forests is about 1% per day (Kimball et al., 2004). It should be noted that the linkage between spring temperature and spring vegetation growth is opposite in some regions, such as parts of Turkmenistan and Uzbekistan where spring NDVI is negatively correlated with spring temperature (Fig. 6a). This may be because the high temperature induced increase in evapotranspiration demand, and this could lead to drought stress, which suppressed spring vegetation growth. Indeed, spring NDVI showed significant positive correlation with spring PDSI in these regions (Fig. 6a).

In summer, our results show that vegetation growth in Inner Asia is generally regulated by the change in PDSI indicated moisture conditions rather than temperature, particularly over the dry regions. This result is consistent with the previous finding from Li et al. (2008) who used eddy covariance techniques, and suggested that soil moisture availability, especially water availability in the upper 20 cm soil layer is the most important controlling factor

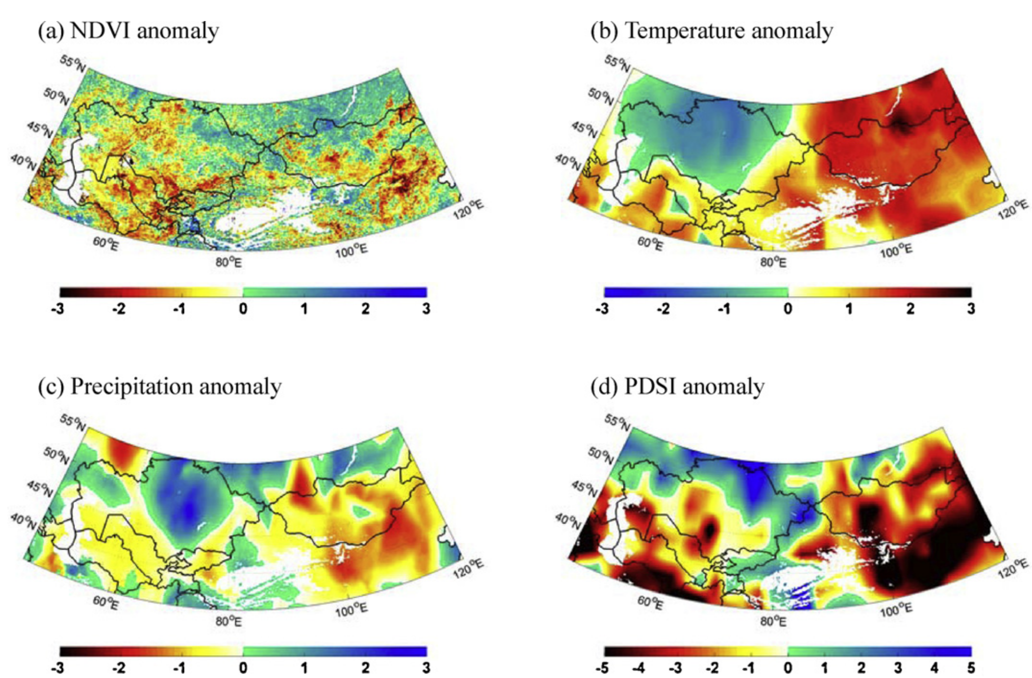

Fig. 8. Spatial distribution of (a) NDVI anomalies (σ_{NDVI}), (b) temperature anomalies (σ_{Tmp}), (c) precipitation anomalies (σ_{Pre}), and (d) PDSI in summer 2001. σ_{NDVI}, σ_{Tmp} and σ_{Pre} for each pixel are calculated according to Eq. (1).

of vegetation productivity of arid steppe ecosystem in Mongolia. In the high altitudes and high latitudes (>50°N), however, a significant positive correlation between summer NDVI and summer temperature was observed (Fig. 6b), suggesting summer vegetation growth in these regions is still limited by temperature. Such enhanced vegetation growth of high altitude regions in response to rising temperature is also observed in the hot and dry summer of 2001 (Fig. 8a). For example, a positive anomaly of NDVI was found in the summer of 2001 over the Altai Mountains, Tianshan Mountains and Pamir Plateau. A similar phenomenon has also been observed in Europe during the 2003 summer heat-wave. Although heat wave induced drought over Europe in 2003 was shown to reduce vegetation growth at the continental scale (Ciais et al., 2005), Jolly et al. (2005) found that vegetation growth over high altitude mountains significantly increased.

5. Concluding remarks

In summary, it is likely that recent spring cooling and increase in summertime drought may have canceled out the fertilization effect of rising atmospheric CO_2 concentration and N deposition on vegetation growth, and thus the greening trend of the 1980s is significantly stalled in the 1990s over Inner Asia. It is important to determine the relative contribution of these factors. Further attribution analyses based on ecosystem process models are needed. The models, however, first must correctly represent changes in limiting climatic factors of vegetation growth across different seasons and regions observed in this study, to reduce uncertainty in the prediction of future trends in vegetation growth. Furthermore, we also found that extreme droughts significantly influence vegetation growth in Inner Asia. The potential for increased frequency of extreme climatic events (e.g., drought) in the future (IPCC, 2007), necessitates studies focused on improving the ability of ecosystem models to represent ecosystem responses to extreme climatic events.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agrformet.2012.09.014.

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